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## DEFECTS OF THE COLOUR-SENSE MECHANISM AS INDICATED BY THE ACCOMMODATION REFLEX

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Our information regarding colour differentiation by the visual mechanism is based mainly upon subjective experiments. The sensations of colour which are studied by these methods are the end-results of the complex chain of events in the visual mechanism commencing with the absorption of light by the visual pigments and culminating at the visual cortex in the processes of perception. Such a chain of processes leaves room for functional abnormalities at many stages. Theoretically there is no more reason to assume that defects in colour vision are caused by abnormalities in the functions of the retinal receptors than by abnormalities at any other stage.

The initiation of those nerve impulses which eventually give rise to visual sensation is, however, not the only function of the retina; it also sends signals to the superior colliculus for distribution to the motor centres for the operation of reflexes. If one of these reflexes can be found to depend upon the differentiation of colour the study of its operation may help us to locate the site of the defects which cause anomalies in colour vision, or at least it may serve to show whether the abnormality of colour sensitivity is retinal in origin.

The accommodation reflex is particularly suitable for this study because its reaction can be watched objectively with some precision. Earlier investigations (Fincham, 1951) showed that the reflex reaction of accommodation to changes in the divergence of the light entering the eye is stimulated by changes in the coloured fringes at the edge of the retinal image due to chromatic aberration (the chromatic stimulus). This was proved by the failure of the reflex in about half the normal subjects examined when the chromatic aberration of the eye was corrected or the object illuminated with monochromatic light. It will be seen that this chromatic stimulus is universally employed in normal vision. The occurrence of accommodative reactions to monochromatic light in many normal subjects is, however, evidence of an additional form of stimulus (the achromatic stimulus).

The existence of two stimuli to the reflex causes some complication because in the subjects in whom both of these stimuli function, the achromatic stimulus would still produce a reaction when defects in colour sensitivity prevent the operation of the chromatic stimulus. However, the tests on those trichromatic subjects who reacted to both chromatic and achromatic stimuli showed that when both stimuli were present the mechanism would react to a smaller object than when, by the use of monochromatic light, the chromatic stimulus was eliminated. Thus we may assume that if in colour-defective subjects the smallest size of object which will produce a response is found to be the same for monochromatic and heterochromatic illumination, the chromatic mechanism is absent. If, on the other hand, this minimum size depends on whether the illumination is monochromatic or heterochromatic, the existence of retinal sensitivity to the components of the heterochromatic light is indicated.

It might be supposed that in cases of abnormal colour vision, and in particular in cone monochromats, the chromatic stimulus to accommodation would be weakened or absent. The purpose of this investigation was the examination of the accommodation reflex in subjects with colour-defective vision to see whether the results would reveal something of the nature of the visual abnormality.

#### METHOD

##### *Apparatus*

An objective study of the changes in the dioptric power of the eye occurring when the divergence of the light from the object is changed has been made by using the coincidence optometer (Fincham, 1936). This instrument enables the user to view the image of a vertical line formed upon the subject's retina. When the object is not conjugate with the retina the upper and lower halves of the image appear to be out of alignment, and the measurement of the refraction of the eye is made by bringing the object to a position conjugate to the retina, when the two parts of the line will appear coincident. The mechanism which in effect moves the object is scaled to read dioptres of refractive error of the eye, and allows changes in power as small as 0.2 D to be measured. In these experiments the change in power due to accommodation was approximately 1.0 D. The reactions were thus easily observed and their speed and precision could be studied. The luminous object or target in the optometer is used for measurement of refraction only, a separate and distant object provided the controlling stimulus for accommodation.

The general arrangement of the apparatus is shown in Fig. 1. The object *O* was at a distance of 4 m from the eye, and consisted of a transilluminated aperture the size of which could be controlled by means of an iris diaphragm. The light from the object was reflected into the subject's eye by the transparent mirror *M*. Because of the inherent difficulty associated with transparent mirrors, namely, the production of a double image, the mirror consisted in this case of a thin prism of a few degrees angle placed with its base-apex line vertical. The result of this was that the two images were so far separated that the subject could view the image from the first surface and ignore the other. Observation with the optometer was made through the mirror, which was so adjusted with regard to the position of the object that when the subject was viewing the latter his visual axis was displaced from the axis of the optometer by about 4°. This meant that all the observations were made at that angular displacement from the fovea, a condition made necessary by the brightness of the light from the optometer target which produced some glare. Two methods of changing the divergence of the light from the object which stimulated the adjustment of accommodation were tested. In the first of these a negative lens was introduced into the path of

the light from the object as close to the eye as possible, but out of the path of the optometer. This is shown at *L* (Fig. 1). In the other method, a small telescope of unit magnification was fixed to the optometer with its axis coincident with the axis of the light from the object and its eyepiece occupying approximately the position of the negative lens *L*. Adjustment of the length of the telescope gave the required change in the divergence of the light from the object at the subject's eye. Although the telescope method produced this change with freedom from the apparent movement of the object which must occur as the lens is dropped into position, its effect was less rapid, and therefore the interposition of the lens has been used as the standard method in the experiments which are described here.

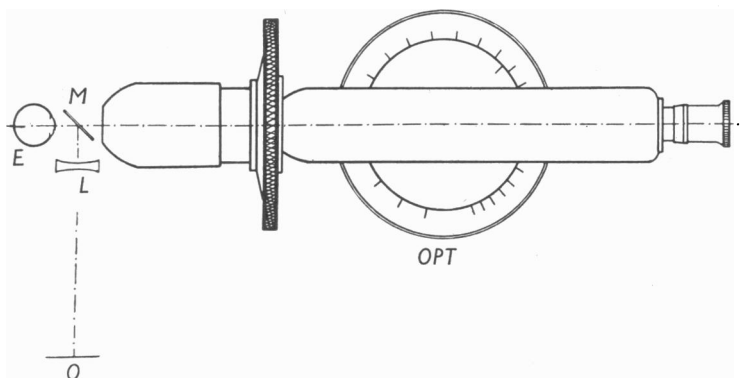


Fig. 1. Plan of general arrangement of apparatus. *OPT*, optometer; *E*, subject's eye; *O*, distant object; *L*, negative lens; *M*, transparent mirror.

The relative operation of the chromatic and achromatic stimuli in the accommodation reflex of normal and colour-deficient subjects was studied by illuminating the object alternatively with monochromatic and heterochromatic light. The two lights chosen for the purpose were both yellow, one produced by a sodium lamp, the other by a mixture of green and red. This choice had the advantage that in testing trichromats, a suitable mixture of green and red can be made which so nearly matches the sodium light that when the illumination of the object is changed from the mixture to sodium, there is no change of colour sensation. Differences in the accommodation reaction must therefore be due to differences in the sensitivity of the reflex mechanism. For the testing of dichromats, again the green + red mixture and sodium can be made to produce a match in both hue and luminance, and therefore a preferential reaction to the mixture would indicate that the mechanism which operates the accommodation reflex was capable of detecting the heterochromacy of the mixture, although in protanopes and deuteranopes the sensations evoked by green and red are the same.

The illumination of the object was provided by three metal vapour lamps arranged in the manner shown in Fig. 2. The sodium lamp was used to give monochromatic illumination, a cadmium lamp was used with a red filter to produce illumination of  $644\text{ m}\mu$  and a mercury lamp with a green filter to give  $546\text{ m}\mu$ . The red filter being placed upon the main axis of the apparatus at an angle of  $45^\circ$  served to reflect from its front surface the green light of the mercury lamp along the axis at the same time as it transmitted the red from the cadmium lamp. In this way the green and red lights were mixed. The mercury and cadmium lamps were fixed at a distance from the achromatic lens *A.L.* conjugate with the subject's eye which was 4 m from the lens. Thus the lamps were imaged upon the eye and the lens was seen in Maxwellian view. This illuminated aperture of the lens served as the object, its size could be varied by the iris diaphragm *D*. The light from the sodium lamp illuminated the matt surface of an opaque white plate *O*. This plate could be lifted out of the system by means of a cord arranged to pass over pulleys and operated

from the position of the optometer. It could also be fixed half-way across the lens aperture so that the subject saw the aperture divided into two halves, the upper half illuminated with sodium light and the lower with the green + red mixture, which enabled the two lights to be compared. The sodium lamp was mounted upon a triangular section slide and could be moved along its axis so that a luminance match could be obtained with the mixture. This part of the apparatus was thus similar in arrangement to the anomaloscope.

In setting up the apparatus the luminance of the mercury green light was reduced by means of a fixed neutral filter of density 0.2 which left the mixture slightly too red and thus adjustable by means of a neutral wedge filter *N.W.* in the path of the light from the cadmium lamp. Adjustment of this filter and the distance of the sodium lamp from the opaque plate permitted a very close match to be made. The desaturation of the mixture was just discernible by the author who has

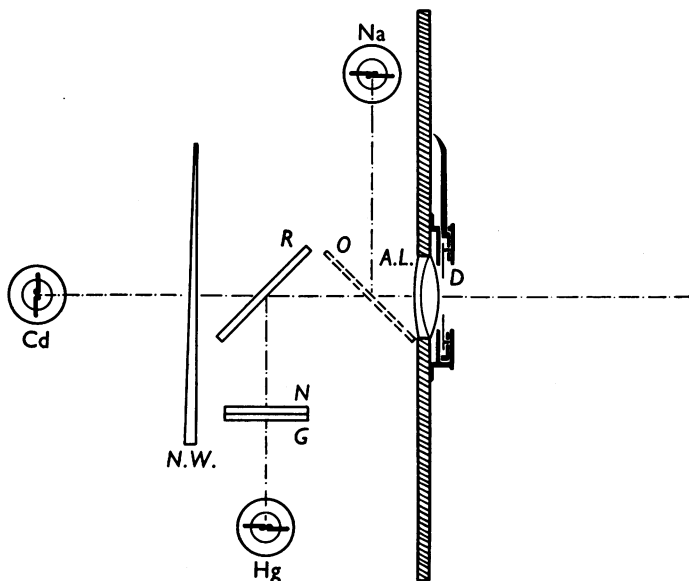


Fig. 2. Plan of illuminating system of object. Na, sodium vapour lamp; Cd, cadmium vapour lamp; Hg, mercury vapour lamp; A.L., achromatic lens; D, iris diaphragm; O, opaque white plate; R, red filter; G, green filter; N, neutral filter; N.W., neutral wedge.

normal trichromatic vision. The match was made with the eye in the position to be occupied by the subject, i.e. with the light reflected into the eye by the transparent mirror *M* (Fig. 1). The field which was used for matching was the full aperture of the lens subtending an angle of  $1^\circ$  at the eye of the subject. The luminance of the object thus seen was 4.5 ft. lamberts approximately. Preliminary experiments showed this to be an optimum brightness for the tests which were to be made and in view of the conditions under which the object had to be observed. Increasing the brightness gave rise to the well-known phenomenon where a bright spot of light of a few minutes diameter, when seen out of focus by the eye, assumes the appearance of a well-defined star or rosette. This is caused by the normal optical defects of the crystalline lens. Such a retinal image does not stimulate accommodation. On the other hand, a less bright object when out of focus was not well seen against the unavoidable glare produced by the strong light of the optometer target.

Illumination of the object with a mixture of blue and green light was also provided. For this purpose the blue lines of the cadmium lamp were used, the red filter being replaced by a blue

filter (Kodak C4), and were added to the mercury green by the same method as that used for producing the green + red mixture. This filter C4 transmits from the cadmium lamp the wavelengths 468 and 478 m $\mu$ . This light was added to the mercury green in such proportions as to produce a distinctly bluish blue-green. The luminances of the three lights employed in the tests, sodium, green + red and blue + green, were equalized. This was done by matching the green + red mixture against the sodium by the method which has been described in which the opaque plate reflecting the sodium light is placed half-way across the lens aperture. The sodium lamp was then kept at the position which gave the balance with the green + red mixture, the red filter before the cadmium lamp was replaced with the blue filter, and the opaque plate was replaced by a sector disk coated with magnesium oxide. Rotation of the disk allowed a comparison of the blue + green and sodium lights by flicker, and a balance was obtained by placing suitable neutral filters in front of the mercury and cadmium lamps. This balance was agreed by two observers, and used throughout the experiments, except for the tests on the cone monochromats, when the luminances were equated for each subject. The equality of the green + red and sodium was adjusted for each trichromatic subject, except C. J. B. and J. P. D., who were anomalous.

### *Subjects*

The trichromatic subjects were all under 30 years of age, approximately emmetropic and with good visual acuity. A preliminary test, to be described later, was carried out in order to select subjects who showed the accommodation reflex to monochromatic as well as to white light. All were males except S. H. and Z. K. Two distinctly anomalous trichromats were included. No preliminary test of the accommodation reaction was made in the case of the dichromats. They were all under 30 years of age with good visual acuity, but in some cases it was necessary to correct their refractive errors.

The colour vision of the dichromats was classified by means of the Ishihara pseudo-isochromatic charts and the diagnosis verified with the 1° diameter bipartite field of green + red mixture and sodium light previously described. In these cases either red or green alone, or when mixed together, could be made to match the sodium light by suitably adjusting the luminances. Marked insensitivity to red light distinguished the protanopes. Of the fifteen dichromatic cases, all males, ten were deuteranopes and five protanopes. In the tests of the accommodation reactions of all the dichromatic subjects, the green + red match for sodium of the normal trichromat was used, but the luminance of the sodium light was adjusted for each subject to effect equality with the mixture.

Three cone monochromats, two males and one female, were also available for these experiments, and fortunately all were found to be suitable in respect of age and visual acuity. For precise information regarding the characteristics of the vision of these subjects reference must be made to the work of Weale (1953). For the present purpose, sufficient evidence of their monochromatism is given by their acceptance of a match of one spectral hue with any other, of whatever wavelength. Their cone vision was proved by the possession of normal visual acuity and the absence of nystagmus and photophobia. In the tests on these subjects the green + red match to sodium light of the normal trichromat was used, the luminances were equated for each subject.

### *Procedure*

The subject's head was held in the head rest of the optometer, and he was directed to view the distant object as seen reflected in the mirror *M* (Fig. 1). The observer then set the optometer to the refraction of the eye by operating the mechanism of the instrument to bring the two parts of the line image into coincidence. Any changes in refraction caused by accommodation could then be seen as a break in the coincidence of the two parts of the line. A negative lens of 1 D was then rapidly interposed into the line of sight of the subject at the position *L*, and the reaction of the accommodation was observed. The lens was then rapidly removed, and the recovery to the original refraction as shown by the parts of the line regaining coincidence was also watched.

In each case an initial test was made with an object subtending an angle of 1° at the eye, and illuminated first with the green + red mixture, and then with sodium light. In the case of trichromats, it was found that the accommodation always responded to the negative lens with the

green + red light, but in some cases not with the sodium light. These cases were eliminated from the experiment as being unsuitable because their reflex mechanism did not respond to the achromatic stimulus. Some of the dichromats showed no response to the negative lens with the object as large as  $1^\circ$  when it was illuminated with either green + red or sodium light. These were recorded as showing no reaction.

After this, the diameter of the object was reduced by means of the iris diaphragm until the eye failed to accommodate when the negative lens was interposed. The subject was then conscious that the object appeared blurred. The minimum size of object was found for which a normal reaction occurred, i.e. accommodation when the lens was interposed and relaxation when it was removed, first with the object illuminated with the green + red mixture and then with sodium light. Later, the same test was made on some subjects using illumination by the blue + green mixture.

To test the accommodative reaction to changes in the colour of the light, which because of the chromatic aberration of the eye will be accompanied by differences of focus at the retina, the apparatus was modified as follows. The negative lens *L* was removed from the cell which held it and by which it could be rapidly swung into, or removed from, the line of sight of the subject. It was replaced by a double-filter holder with a blue and a red filter mounted side by side so that the same simple mechanism which had been used to swing the lens into position now caused either the blue or red filter to be brought into the subject's line of sight. The object consisted of the full  $1^\circ$  diameter of the lens *A.L.* (Fig. 2) illuminated with a tungsten lamp. Upon the lens were placed a number of circular black spots of about  $4'$  diameter to serve as detail for the eye to focus upon. The blue filter was then brought into position so that the object appeared blue to the subject. As the eye was myopic to blue light a  $-0.5$  D lens was placed upon the line of sight close to the filter and gave clear vision of the object. The experiment consisted in rapidly exchanging the blue filter with the red one and watching for any change in the refractive power of the eye with the optometer. The filters used were Ilford no. 666, bright spectrum blue, transmitting the short wave-length up to  $535\text{ m}\mu$ , and Ilford no. 205, tricolour red, transmitting from  $640\text{ m}\mu$  to the infra-red.

#### RESULTS

By making the test of the response to the negative lens with an object of about  $15'$  diameter it was possible to judge the rate and precision of the reactions of both accommodation and relaxation normal for the individual. The size of the object was then reduced by a few seconds of arc, and again the reactions were noted when the negative lens was interposed and removed. It was found in most cases that, as the size of object approached that for which no reaction of accommodation occurred, the rate and amplitude of the response decreased, and the accommodation did not relax when the lens was removed. A typical end-point for the reaction was as follows:

Object size	Accommodation	Relaxation
$6'$	Normal	Normal
$5'$	Slow	Nil
$4'$	Nil	Nil

The values recorded in the tables were the minimum size for which the reactions were normal. The tests were repeated on some of the subjects at later dates, and it was found, without exception, that the results were substantially the same. The value for the minimum effective size could be altered by altering the brightness of the object, but the recorded results were all obtained with approximately constant luminance of  $4.5\text{ ft.L.}$

The minimum effective angular size of test object for a number of subjects with trichromatic vision is given in Table 1. In every case the figure for the mixture of monochromatic lights is lower than that for sodium, indicating the operation of both the chromatic and achromatic stimuli to accommodation.

Two of the subjects submitted for test as dichromats were found to have trichromatic vision. C. J. B. was deuteranomalous. When shown the normal matching field of green + red and sodium light, he described the mixture as red and the sodium as green. J. D. D. was protanomalous. He required much more than the normal proportion of red in the green + red mixture to make

TABLE 1. Trichromats  
Minimum effective angular size of object (minutes of arc)

Subject	Green + red	Blue + green	Sodium
R. F. D.	4	—	6
D. G. C.	2	—	7
B. G.	2	—	5
*C. J. B.	8	—	11
†J. D. D.	10	—	13
K. J. A.	3	—	6
R. D. G.	4	—	6
J. T. C.	3	—	5
D. E. M.	3	—	5
R. D. M.	3	3	8
B. H. W.	2	5	6
H. A. St J.	2	4	6
A. C. B.	4	8	8
S. H.	4	9	9
H. B.	2	3	5
N. G-H.	3	3	4
Z. K.	4	4	6
J. C. S.	2	2	5
P. W. J.	3	6	6
J. D. H.	3	3	5

\* Deuteranomalous.

† Protanomalous.

a match with the sodium light. In these two trichromatic cases only, the proportions of red to green found by the author to match the sodium light were used for the test, as it was considered that the proportions adopted by the subjects would not contain sufficient of each of the colours to show the effect of chromatic aberration for the purposes of the experiment.

Table 2 gives the minimum effective angular size for a number of subjects with dichromatic vision. The similarity of values when either a mixture of monochromatic lights or sodium is used indicates that only the achromatic stimulus is operative in these cases.

From Table 3, however, which gives results for three subjects with monochromatic vision, it seems that the accommodation reflex is behaving in a way similar to that in normal subjects.

In all the monochromatic cases the eye accommodated when the colour of the object was changed from blue to red and returned to its normal power

when the light from the object was again made blue. The change in the refraction of the eye was measured with the optometer. In subject T. E. A. B. it changed from 0 with the blue object to  $-0.6$  D with the red object; in the other subjects the corresponding readings on the optometer were 0 and  $-0.7$  D. It should be mentioned here that this instrument is scaled to read the power of the lens required to correct the eye, so that the negative sign shows that the dioptric power of the eye has increased.

TABLE 2. Dichromats

Subject	Type of defect	Minimum effective angular size of object (minutes of arc)	
		Green + red	Sodium
B. D.	Deuteranope	No reaction	No reaction
W. R. B.	Protanope	No reaction	No reaction
C. J. D.	Deuteranope	No reaction	No reaction
D. L. S.	Deuteranope	No reaction	No reaction
G. L. W.	Protanope	No reaction	No reaction
B. M.	Protanope	No reaction	No reaction
E. M. O.	Deuteranope	No reaction	No reaction
H. L.	Deuteranope	6	6
G. R. M.	Deuteranope	4	4
D. H. S.	Deuteranope	3	3
E. H.	Protanope	5	5
G. K. C.	Protanope	10	10
D. G. H.	Deuteranope	5	5
D. E. C.	Deuteranope	5	5
D. E. J.	Deuteranope	2	2

TABLE 3. Cone monochromats

Subject	Minimum effective angular size of object (minutes of arc)		
	Green + red	Blue + green	Sodium
J. G. (F)	4	4	6
T. E. A. B. (M)	4	6	6
A. R. J. (M)	2	3	4

## DISCUSSION

Regarding the actual results, there is little more to say in respect of the trichromats. The tests were made upon them mainly as a control in order to establish that the reflex mechanism does react to a smaller object when both the chromatic and achromatic stimuli operate than when the achromatic stimulus only is used. There are, however, two points of interest in this series of results. In general, the reflex mechanism does not react so well to a mixture of blue and green light as to one of green and red of the same luminance. The effect of chromatic aberration upon the retinal image will be present with the blue + green illumination; in fact, the difference in focus is greater in this region of the spectrum. The reason for the difference in the reaction is thought to be the relative insensitivity of the central fovea to blue light (König, 1894). The other point of interest was the behaviour of the two anomalous trichromats (C. J. B. and J. D. D., Table 1). Although the sensation they derived from



the mixture of green and red light was quite abnormal, showing that one of them had a low sensitivity to red and the other to green, their accommodation reflex mechanism used the effects of chromatic aberration in the retina as efficiently as that of normal subjects. The indication here is that the abnormality is in a part of the visual pathway above the point at which the afferent impulses to the reflex mechanism leave those to the visual cortex and so the reflex is unaffected.

The results obtained with the dichromats are quite different. In the eight cases which accommodated when the divergence of the light from the object was increased, the minimum effective size of the object was equal for the green + red mixture and monochromatic yellow illumination. The reflex mechanism in these subjects appears to make no use of the colour fringes in the retinal image caused by chromatic aberration, as a stimulus controlling accommodation; only the achromatic stimulus is effective. Most of the dichromats were tested also with the object illuminated with white (tungsten) light and with the blue + green mixture. In each case the minimum effective size of object was the same as with the sodium light. In the previous study of the reactions of a large number of trichromatic subjects (Fincham, 1951) it was found that about 50 % showed no reaction when the object was illuminated with monochromatic light, i.e. their reflex mechanism responded to the chromatic stimulus only. Subjects with this characteristic were not included in the group of trichromats used in the present experiments. Among the dichromats, however, it was found that seven out of fifteen showed no accommodative reaction to changes in the divergence of the light from the object. The explanation is that these subjects, like those just mentioned among trichromats, have not developed the mechanism which reacts to the achromatic stimulus, the only type of stimulus of this reflex which is effective in dichromatic vision.

We must conclude from the results of this test that in dichromats the retina does not send differential colour impulses to the reflex centres of the mid-brain as does the trichromatic retina. It appears, therefore, that the defect in these subjects is retinal or at least in that part of the neural chain which is common to the path to the superior colliculus and the lateral geniculate body. The subjects which were tested were protanopes and deuteranopes and, while it is understandable that in such cases the aberration fringes of a green + red retinal image may not be detected, the lack of preferential response to a white or blue + green object is not accounted for by the absence of green + red differentiation. A possible explanation is that the response to the chromatic stimulus to the reflex has not been developed because the range of wavelengths within which the dichromatic visual mechanism could use the aberration fringes to control accommodation reflex is so restricted. A more probable cause, however, is the absence of colour sensitivity of the central fovea of

red-green-blind subjects. The stimulus to the accommodation reflex arises from a very small central area of the retina; earlier experiments showed this to be less than 6' radius from the point of fixation. It has been shown by Willmer (1949) that the central fovea of the red-green-blind subject is monochromatic, which will account for the complete absence of chromatic stimuli to accommodation in these cases.

A remarkable feature of the present results is that unlike the dichromats, the cone monochromats behaved like subjects with normal colour vision in that the minimal size of stimulus was less when it was heterochromatic than when it was monochromatic. This is at first a most surprising fact when it is considered that these subjects have no perception of colour. Provided the image is out of focus their reflex mechanism can detect the difference between a green + red mixture and a sodium light which give the same sensation to normal trichromatic vision. Unlike the dichromats, the monochromats retinæ react to, and signal to the mid-brain, the difference between green and red light as it appears in the narrow fringes caused by chromatic aberration when the green + red image is slightly out of focus. The defect which causes the vision of these subjects to be achromatic must therefore be situated, not in the receptor layer of the retina, but in those parts of the visual pathway above the point at which the impulses to the reflex centres in the mid-brain leave those concerned with sensation. It seems probable, therefore, that the defect is in the cortex.

The recorded reaction of the accommodation reflex in the monochromats to changes in the focus of the retinal image produced by changing the colour of the object from blue to red of course gives no information regarding the subject's colour mechanism. The reflex reacted because the red light was convergent on striking the retina. The results are interesting when compared with the behaviour of most normal subjects, in which the change from blue to red light produces an out-of-focus image, and the accommodation reflex is not stimulated to correct it. The explanation of the non-reaction of accommodation to this change in most normal subjects could be that, because of the chromatic aberration of the eye, differences of definition of the retinal image are the normal accompaniment of differences of colour. This suggests the existence of a compensating mechanism by which the change of colour signals received by the cortex are correlated with the impulses to the mid-brain, which without this compensation would initiate the reflex reaction of the ciliary muscle. Because in the monochromat there is no sensation of colour, such a compensating system cannot exist and the accommodation reacts to differences of focus of the light at the retina, whether caused by differential focusing for colour or not.

In support of this an interesting phenomenon found to occur with the monochromatic subject, A. R. J., may be mentioned. This subject claimed to

be able to detect the colour red under certain conditions, and during the experiment he was asked if he could name the colours of the filters that were being used. Without hesitation he named the red filter correctly every time it was presented, but could only say that the blue filter was not red. This suggests that the accommodation centre in the mid-brain can signal its reactions to the cortex in some way.

The causes of abnormal colour vision are unknown, but the experiments which have been described appear to throw some light upon the site of the defects in the neural system. They show that the various types of defect are distinct in their origin and may arise from different causes. They are not merely varying degrees of the same abnormality.

#### SUMMARY

1. The accommodation reflex to changes in the divergence of the light from the object is stimulated by alterations in the coloured fringes of the retinal image due to chromatic aberration of the eye.

2. The reflex mechanism also reacts to another form of stimulus which does not depend upon colour sensitivity. By illuminating the object alternatively with monochromatic light and a heterochromatic mixture which matches it, the relative effectiveness of the chromatic and achromatic stimuli can be tested.

3. This test has been applied to normal trichromats, dichromats and cone monochromats, and has shown that in red-green-blind subjects the accommodation reflex mechanism is not stimulated by the effects of chromatic aberration. In cone monochromats the chromatic stimulus operates in the same way as in normal trichromats.

4. These results are evidence that red-green blindness is retinal in origin because, in addition to the defect in sensation, the reflex centre is not innervated by impulses arising from red-green differentiation. In the cone monochromats which were tested, impulses derived from colour difference were sent to the reflex centre in the mid-brain. The site of the colour defect in the monochromats was therefore above the zone at which the paths to the mid-brain concerned with reflexes leave the visual paths to the cortex.

The author wishes to express his indebtedness to Mr R. A. Weale for introducing to him the very rare monochromatic subjects and also for many helpful discussions. Thanks are also due to all those who acted as subjects and particularly to the monochromats, Mrs J. Grant, Mr A. R. Jackson and Mr T. E. A. Barclay, each of whom travelled considerable distances on several occasions to give their services.

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